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A workshop on "Formal Models for Intelligent Control," jointly funded by the Army Research Office (ARO) and the National Aeronautics and Space Administration (NASA), and jointly sponsored by the Center for Intelligent Control Systems (CICS) and the University of California at Berkeley's Intelligent Machines and Robotics Laboratory, was held at M.I.T. during 30 September--2 October 1993. The workshop brought together a large number of researchers and specialists from universities, the government, and industry, providing a stage for interesting presentations as well as lively discussion.

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FINAL REPORT

Workshop on Formal Models for Intelligent Control

A workshop on "Formal Models for Intelligent Control," jointly funded by the Army Research Office (ARO) and the National Aeronautics and Space Administration (NASA), and jointly sponsored by the Center for Intelligent Control Systems (CICS) and the University of California at Berkeley's Intelligent Machines and Robotics Laboratory, was held at M.I.T. during 30 September--2 October 1993. The workshop brought together a large number of researchers and specialists from universities, the government, and industry, providing a stage for interesting presentations as well as lively discussion.

General Principles and Case Studies

A number of papers discussed general characteristics of intelligent control systems, and several presented case studies.

In his paper "What is Intelligent Control?" Shankar Sastry of the University of California at Berkeley and Harvard University focussed on recent changes in the field of control, communications, and systems in view of the rapid advances in computing technology. The opportunities that have come to light are somewhat different in character from those previously encountered, and have been popularized recently under the title of Intelligent Control, which Sastry described as referring to the hierarchical organization of the control of complex systems, with fan-in of sensor data and fan-out of actuator commands. Control and models for control are signal based at the lowest levels of the hierarchy and symbolic or event based at higher levels. The dynamics of such systems are a rich blend of automata, discrete event systems, petri nets and differential equations. Examples of such systems occur, for instance, in biological motor control, in intelligent vehicle highway systems, in flight control and automotive control, and in signal processing. Sastry characterized some common features of these examples, namely hybrid dynamics consisting of continuous time dynamics combined with logic; hierarchically-organized control, with nonlinear control at the level of differential equations at the lower layers, and stochastic control of finite-state non-deterministic processes analogous to the control of Markov chains at the higher layers; and distributed intelligence and adaptation at all levels of the hierarchy.

Sanjoy K. Mitter of M.I.T., a co-director of the CICS, presented a paper entitled "Steps Towards Real Intelligence," in which he discussed why the methodology of classical Artificial Intelligence (AI) is not the appropriate one for the design of control systems having diverse sensory inputs and a variety of output modalities. He contrasted that methodology with recent work on pattern theory by Ulf Grenander, David Mumford, Mohammed Akra, and himself, emphasizing its relevance to the design of layered hierarchical control systems. (A summary of this paper appears elsewhere in this Newsletter.)

A case study was presented by Pravin Varaiya of the University of California at Berkeley, in his paper entitled "Hybrid Models for Intelligent Vehicle Highway Systems." Stressing that

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proponents of Intelligent Vehicle/Highway System or IVHS see it as a new technology that will make a major improvement in highway transportation, Varaiya explained how control, communication, and computing technologies will be combined into an IVHS system that can significantly increase safety and highway capacity without building new roads. He outlined key features of one highly automated IVHS system, and proposed a hierarchical control architecture for it. He suggested hybrid models for the specification and verification of the control system design, and showed how existing software can be used to verify some limited features of the design. He concluded by pointing to open problems in theory and software support.

Another case study was discussed by George Meyer of the National Aeronautics and Space Administration (NASA), in his paper "Modeling of Flight Vehicle Management Systems." He defined Flight Vehicle Management System (FVMS) as the on-board systems encompassing all automatics linking the human pilot and the air traffic control (ATC) to the actuators and sensors of an aircraft. The function of FVMS, according to Meyer, is to interpret, adapt, refine, and execute the commands from the human pilot and ATC, and to provide aircraft status information feedback to both the pilot and the ATC. The complete control system composed of the human pilot, ATC and FVMS is both hybrid and reactive. Rigorous techniques for the systematic modeling, design and analysis of such systems are just emerging in the field at large. Meyer explored the application of such methods to the specific case of the FVMS, starting with an overview of the problem, and continuing with a description of the structure of a generalized multi-mode auto pilot, which provides guidance, navigation and control. Stating that the function of the auto pilot is to transform tables of control points and estimates of aircraft state and wind into actuator commands, Meyer concluded by outlining a top-down approach for the modeling and design of the subsystem transforming the commands from human pilot and ATC into the tables of control points that drive the auto pilot.

In his paper entitled "Intelligent Aircraft/Airspace Systems," Robert Stengel of Princeton University presented a concept for an Intelligent Aircraft/Airspace System (IAAS) that could be a focal point for developing air traffic management in the coming decades. Air transportation provides the backbone for passenger transport over moderate to long distances in the U.S. and much of the world, and is becoming increasingly important for short-range travel and cargo transport as well. There is a growing demand for use of available airspace and a heightened concern for on-time performance. Demand frequently exceeds available capacity of the airspace system, causing flight delays, negative economic impact, and passenger inconvenience. New technologies are emerging that will make flight operations both simpler and more complex: on the one hand, advances hold promise for increasing the productivity, reliability, and safety of the air transportation system; on the other, advances in technology introduce uncertainty, increase human workload and the potential for dispute, and present new challenges for both certification and day-to-day operations. The IAAS introduced by Stengel would integrate the capabilities of all ground-based and airborne components of the system (identified as Intelligent Agents) in order to provide increased capacity and maintained or improved safety. He proposed Principled Negotiation as a framework for interactions between intelligent agents.

John Hauser of the University of Colorado spoke about "Challenges in Flight Control," arguing that the pursuit of high performance and maneuverability in aerospace vehicles continues to present difficult challenges to the control system designer: not only must future vehicles be capable of rapid transitions over a large operating envelope, but they must also be able to accommodate a variety of mission objectives and different physical aircraft configurations. Using a simple aircraft model, Hauser discussed several of these issues and provided some techniques that may be used to help guarantee successful operation of such aircraft.

Discrete Event and Hybrid Systems

Several papers presented during the Workshop were dedicated to Discrete Event Dynamic Systems (DEDS), examples of which range from large international airports to computer communication networks, manufacturing plants, logistics and service systems, and C3I systems, and to hybrid systems, i.e. systems that include both discrete- and continuous-time subsystems that interact with each other.

In his talk entitled "Failure Diagnosis Using Discrete Event Models," Stephane Lafortune of the University of Michigan described ongoing work on the problem of failure detection and diagnosis for large complex systems such as Heating, Ventilation, and Air Conditioning (HVAC) systems. He proposed an approach where the system is modeled using a logical (or untimed) discrete event model (LDEM), and where the different failures to be diagnosed are represented by different types of unobservable events. Lafortune outlined a methodology for building such models, defining the notion of "diagnosability" of a model (i.e. of the formal language generated by an LDEM) in terms of properties of this language involving suffixes of traces that contain failure events, and describing necessary and sufficient conditions for diagnosability. He argued that the notion of diagnosability is related to, but distinctly different, from the notions of observability and invertibility previously addressed in the discrete event literature. Using an example of a small HVAC system, Lafortune illustrated how to perform system diagnosis using an appropriately built finite state machine he called a "diagnoser."

Yu-Chi Ho of Harvard University spoke of "A Formal Model for Heuristic Rules in DEDS," stressing that while optimality in design represents the holy grail of engineering, it is perhaps often an ideal but unattainable or not cost-effective goal. Ho argued that the modern world is full of complex system optimization problems that cannot be solved, such as Discrete Event Dynamic Systems problems in manufacturing automation and other complex man-made systems. He proposed to re-direct the optimization goal and ask "softer" questions, so as to lead to a quantitative model for heuristics and other ad hoc decision rules.

Moving on from DEDS to hybrid systems, Roger Brockett of Harvard University discussed "Representation of Data for Sensing, Communication, and Control." He pointed out that much of the value of novelty associated with neural networks, fuzzy logic, and expert systems as applied to control problems can be thought of as coming from new ways to represent the data summarizing past history, the possible control actions, the feedback laws, etc. Viewed in this way, these approaches to control suggest that a broader investigation of the question of how one can best represent data for control purposes could lead to broad framework in which these methods of control could be more usefully compared with other alternatives and might even suggest entirely different alternatives. Brockett introduced a new class of models designed to emphasize the role of data representation in control. These models permit one to establish the relative performance of a wider variety of systems than is possible using standard approaches, and build upon recent work on hybrid systems.

In his paper entitled "Hybrid System Modeling, Analysis, and Design," Panos J. Antsaklis of the University of Notre Dame began by summarizing the main ideas and concepts of intelligent autonomous control, and discussing their relation to hybrid control. He introduced quantitative models for hybrid control systems that can serve to identify fundamental concepts, analyze and understand important properties, and design controllers that meet control goals while satisfying the design constraints, including models of the plant, controller, and interface. He also discussed computationally-efficient design methods, such as convex programming, learning algorithms, and approaches to integrating prior operator experience with engineering models of the plant, and proposed a basic framework consisting

of the translation of engineering specifications and operator procedures into DES models, the design and validation of the DES controller, and its translation to operator procedures.

Anil Nerode of Cornell University also addressed hybrid control in his paper entitled "Automatica from Covers and Optimal Control," where he defined hybrid systems as networks of digital programs and continuous plants under the influence of external disturbances, and hybrid control as the control of continuous plants by sequential automata. Pointing out that this usually entails frequent changes (based on sensor measurements of the trajectory) in the continuous conventional control law applied to the plant, yielding plant trajectories without smooth tangents at the discrete times when the control law ordered by the control program changes, Nerode stressed that how and when to make these control law changes is the business of the sequential automaton. He went on to discuss a uniform model of hybrid systems as networks of automata intended to cover all variants of the notion of hybrid system in use by others.

In his paper "Logic Control via COCOLOG" Peter Caines of McGill University introduced the COCOLOG (Conditional Observer and Controller Logic) system as a partially ordered family of first order logical theories expressed in the typed first order languages describing the controlled evolution of the state of a given partially observed finite machine. He described a restricted version, called a system of Markovian fragments of COCOLOG, in which a smaller amount of information is communicated from one theory to the next. These are associated with a restricted set of candidate control problems. Under weak conditions, a Markovian fragment theory includes the state estimation theorems of the corresponding full COCOLOG system, and, for a certain set of control rules, has what is termed the same control reasoning power. This supplies a theoretical basis for the increased theorem proving efficiency of the fragment systems versus the full COCOLOG systems. Caines concluded with some computer generated examples illustrating these results.

Peter Ramadge of Princeton University spoke of "Models for Discrete-Event and Hybrid Systems." Several formal models have recently been proposed for the control of a dynamical system in a hybrid framework; at the most elementary level these systems model what might result from several forms of "intelligent control." Simple case studies of flow models have illustrated the complex nature of the closed loop dynamics, and results from the computer science community have attempted to determine the computation complexity of simple questions concerning the behavior of such systems. Ramadge reviewed some of these models and results and speculated on what connections can be made between them.

Michael Heymann of the Technion presented a paper entitled "From Discrete Event Processes to Hybrid Systems," in which he argued that hybrid systems may be viewed as objects consisting of two communicating modules: a reactive module, in which discrete state changes occur in response to events that are generated either internally or by the environment, and a transformational module that responds temporally to discrete or continuous-time signals. In the most general case, the two modules are strongly intertwined and affect each other's internal operation; in simpler situations, which Heymann called unilateral hybrid systems, only one of the modules is affected by the operation of the other. In the simplest version of such systems, the reactive module of the system consists of a Discrete Event Process (DEP), i.e. a simple state transition system, but in general the reactive module may be more complex. The transformational module of the system is generally a (continuous-time or discrete-time) dynamical system in which changes occur in response to time evolution. Heymann considered four classes of systems: DEP, (statically) timed DEP, dynamically timed DEP, and (fully) hybrid systems. In contrast to the first three classes of systems which are unilateral (only the reactive module is affected by the

transformational module when it exists), in the fully hybrid system the transformational module is also effected by the reactive module.

A.S. Morse of Yale University presented a paper entitled "Logic-Based Switching: A Form of Intelligent Control," in which he described three different hybrid systems comprised of logic-based switching strategies, together with the processes they are intended to control, each consisting of a continuous-time process to be controlled, a family of continuous-time, candidate fixed-parameter or adaptive controllers, and an "event-driven switching logic." The first two logics, respectively called hysteresis switching and dwell-time switching, are simple strategies capable of determining in real time which candidate controller should be put in feedback with a process in order to achieve desired closed-loop performance. The third, called cyclic switching, has been devised to deal with the well-known certainty equivalence stabilizability problem which arises in the synthesis of identifier-based adaptive controllers because of the existence of points in parameter space where the design model upon which certainty equivalence synthesis is based loses stabilizability.

In his paper "A Dynamicist's View of Hybrid Systems," John Guckenheimer of Cornell University presented a formal mathematical definition of hybrid systems that has been implemented in a version of the computer package DsTool. He used an example, stabilizing an inverted double pendulum on a cart, to show the effectiveness of hybrid control strategies for solving problems that have proved difficult with more traditional methods. Guckenheimer also commented on ongoing work to develop a general theory of the dynamics of two-dimensional hybrid systems.

Robert Grossman of the University of Illinois presented "Trajectory Stores and Hybrid Systems," a paper concerned with a proof of concept implementation of a path planning algorithm for hybrid systems, based on creating a persistent object store consisting of short-duration trajectory segments, and computing the desired path by a suitable query on the store. The query returns a concatenation of short-duration trajectory segments which is close to the desired path; these segments are computed by using a divide and conquer algorithm to break up the original path into shorter paths, each shorter path being matched to a nearby trajectory segment which is part of the persistent object store by using a suitable index function. In order to obtain near-real time performance, a scalable persistent object store was developed and optimized for scientific computing in high performance computing environments. The hybrid system is described in observation space representation, which may be viewed the dual of state space representation, and has the advantage of defining the system as suitable products of continuous nonlinear control systems and discrete automata. Grossman pointed out that this algorithm trades space for time, in that while large amounts of space are required to store all the pre-computed trajectory segments, the cost to approximate the path is low.

Wolf Kohn of Intermetrics, Inc. spoke about "Multiple Agent Hybrid Control Systems," presenting an overview of a formal approach for the design, analysis, and implementation of hybrid control systems, which are characterized by the presence of at least one reasoning module, i.e. a device whose function is to infer from stored dynamic or static knowledge a course of action. Such modules, or hybrid controllers, necessary elements in the implementation of autonomous systems, and their main distinguishing functional characteristic with respect to conventional control systems is the ability to redesign on-line the control law. This capability is needed for a variety of reasons such as responding to unexpected behavior of the system or its environment, improving performance when enhanced knowledge about the system or its environment become available through sensory observation, responding to changes in the goal of the system, decreasing the behavioral effects of structural uncertainty, etc. Kohn focussed on Declarative controllers, in which intelligence is provided by a reasoning procedure whose central element is a customized

Equational Logic Inferencer. He described the main operational characteristics of Declarative Controllers, illustrating them with examples, and presenting some preliminary results about their structure and dynamics.

Neural and Fuzzy Systems

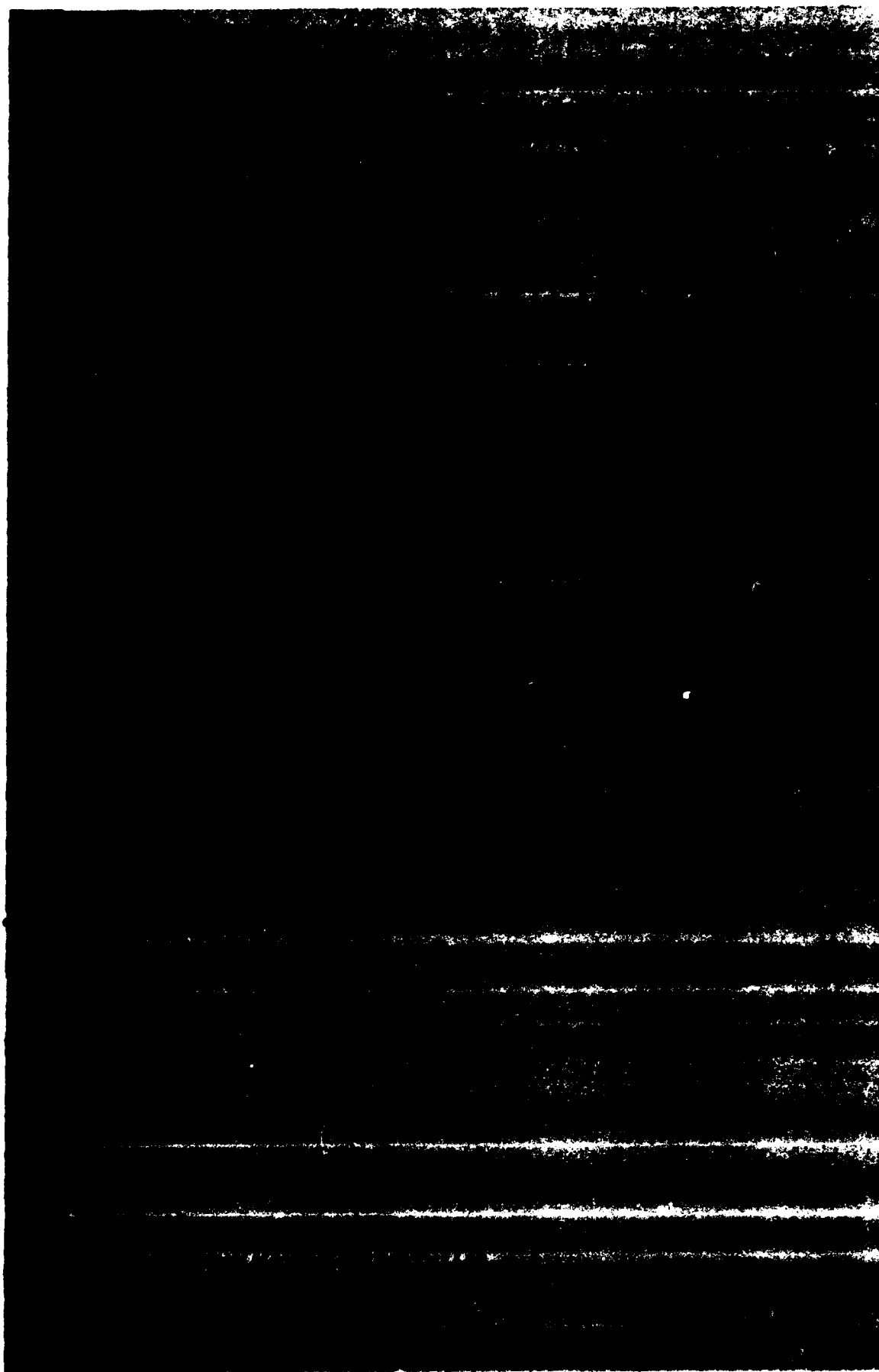
Finally, some papers focussed on neural networks and fuzzy systems in the context of intelligent control.

In his paper "Dynamic Systems and Analog Computation," Eduardo Sontag of Rutgers University argued that one of the most exciting challenges in current control theory and signal processing is formulating a rich mathematical framework in which to study the interface between the continuous (analog) world and discrete (digital) computers which are capable of symbolic processing. Successful approaches allowing for the interplay of modern control with automata theory and other techniques from computer science are needed, he stated, because, although classical control techniques have proved spectacularly successful in automatically regulating relatively simple systems, in practice controllers resulting from the application of that well-developed theory are often used as building blocks of far more complex systems; the integration of these systems is often accomplished by means of ad-hoc techniques that combine pattern recognition devices, various types of switching controllers, and humans (or, more recently, expert systems) in supervisory capabilities. The need to understand the analog/digital interface has motivated much research into areas such as discrete-event systems, supervisory control, and more generally "intelligent control systems," and in this context, it is of interest to study the behavior of dynamical systems from the point of view of classical computational theory. Sontag described recent work on the study of dynamical systems as analog computing devices, as well as some related issues such as the observability of continuous systems with restricted observations, and control and pattern recognition by neural nets.

Masayoshi Tomizuka of the University of California at Berkeley presented an overview of "Fuzzy Control in the Control Engineer's Tool Box." He stressed that although the controlled plant and control objectives must be well understood for the design of control systems, there is no universally best methodology for solving every problem. While the fuzzy-rule-based or fuzzy-logic approach, which has proven its worth in the design of certain control systems, is often referred to as fuzzy control, it has two components: "rule or logic base" and "fuzzy set theory." Expert knowledge or good ideas can often be described by a set of rules; fuzzy set theory provides a means of transforming a set of rules to a computer-implementable control algorithm. The designer must have a model (implicit model), although it may not be in the form of a differential equation, and the fuzzy set is a friendly interface to humans to describe and convert their knowledge to control algorithms. Tomizuka argued that fuzzy logic is an attractive method for higher level controls such as coordination of various sub-controllers, each of which is designed for a different objective, and that increasing attention is being directed to the blending of conventional control and fuzzy control, as in the case of the use of fuzzy boundaries in gain scheduling and variable structure systems.

In a paper entitled "Modeling and Control of Hierarchical Systems with Fuzzy Logic," L.X. Wang of the University of California at Berkeley stressed that fuzzy systems have a dual role: on one hand, they are rule-based systems constructed from a collection of fuzzy IF-THEN rules, while on the other, they are nonlinear mappings which have nice mathematical properties like universal approximation. One contribution of fuzzy logic is that it provides a systematic procedure of transforming a rule base into a nonlinear mapping. Wang used fuzzy systems to model higher levels of hierarchical systems, considering three-level hierarchical systems where the lowest level comprises the plant and conventional feedback controllers, the middle level performs supervisory operations to guarantee the stability of the whole system,

and the top level is a planning level which provides control targets for the lower levels and communicates with the environment. The plant is modeled by differential equations, and the supervision and planning levels are modeled by fuzzy systems. The advantage of such model is that all the levels are formulated in the same mathematical framework (due to the dual role of fuzzy systems), making it possible to analyze the hierarchical systems in a mathematically rigorous fashion. Wang focussed on two theoretical questions introduced by this model, how to specify the supervisory rules (i.e. how to design the fuzzy systems modeling the supervision level) such that the whole system is stable, and how to design and update the fuzzy systems modeling the planning level such that the whole system achieves its objectives and is adaptable to new environment and new objectives, and presented two case studies, intelligent vehicle/highway systems, and integrated planning/control of mobile robots.



**Thursday, September 30, 1993
(morning)**

**Introductory Session:
Representative Systems**

9:00 - 9:30

What is Intelligent Control?
Shankar Sastry
University of California

9:30 - 10:00

Steps Towards Real Intelligence
Sanjoy Mitter
MIT

10:00 - 10:45

Hybrid Models for Intelligent
Vehicle Highway System
Pravin Varaiya
University of California

10:45 - 11:00 Coffee Break

11:00 - 11:45

Modeling of Flight Vehicle
Management Systems
George Meyer
NASA

11:45 - 12:30

Failure Diagnosis Using Discrete
Event Models
Stephane Lafortune
University of Michigan

12:30 - 1:30 Lunch

**Discrete Event and Hybrid Systems
(afternoon)**

1:30 - 2:15

A Formal Model for Heuristic
Rules in DEDS
Yu Chi Ho
Harvard University

2:15 - 3:00

Representation of Data for Sensing,
Communication, and Control
Roger Brockett
Harvard University

3:00 - 3:45 Discussion

3:45 - 4:00 Tea Break

4:00 - 4:45

Hybrid System Modeling,
Analysis and Design
Panos J. Antsaklis
University of Notre Dame

4:45 - 5:30 Discussion

**Friday, October 1, 1993
(morning)**

Hybrid Systems

9:00 - 9:45

Automatica from Covers and
Optimal Control
Anil Nerode
Cornell University

9:45 - 10:30

Logic Control via COCOLOG
Peter Caines
McGill University

10:30 - 10:45 Coffee Break

10:45 - 11:30

Models for Discrete-Event and
Hybrid Systems
Peter Ramadge
Princeton University

11:30 - 12:30 Discussion

12:30 - 1:30 Lunch

Switched Systems (Afternoon)

1:30 - 2:15

Logic-Based Switching: A Form
of Intelligent Control
A.S. Morse
Yale University

2:15 - 3:00

A Dynamicist's View of Hybrid Systems
J. Guckenheimer
Cornell University

3:00 - 3:45

Dynamic Systems and Analog
Computation
Eduardo Sontag
Rutgers University

3:45 - 4:00 Tea Break

4:00 - 4:45

Trajectory Stores and Hybrid
Systems
Robert Grossman
University of Illinois

4:45 - 5:30 Discussion

**6:30 Buffet Dinner at the
MIT Museum**

**Saturday, October 2, 1993
(morning)**

Representative Systems

9:00 - 9:45

Michael Heymann
Technion

9:45 - 10:30

Intelligent Aircraft/Airspace
Systems
Robert Stengel
Princeton University

10:30 - 10:45 Coffee Break

10:45- 11:30

Multiple Agent Hybrid Control System
Wolf Kohn
Intermetrics Inc.

11:30 - 12:15

Challenges in Flight Control
John Hauser
University of Colorado

12:00 - 1:00 Lunch

**Neural & Fuzzy Systems--Soft
Computation
(afternoon)**

1:30 - 2:15

Fuzzy Control in Control Engineer's
Tool Box
Masayoshi Tomizuka
University of California

2:15- 3:00

Modeling and Control of Hierarchical
Systems with Fuzzy Logic
L.X. Wang
University of California

3:00 - 3:45 Discussion

3:45 - 4:30 Tea Break

ABSTRACTS OF PRESENTATIONS

Thursday, September 30, 1993

Introductory Session: Representative Systems

9:00 - 9:30

What is Intelligent Control?

Shankar Sastry

University of California

The field of control, communications and systems has changed in view of the rapid advances in computing technology. The opportunities that have come to light are somewhat different in character from those previously encountered and have been popularized recently under the title of Intelligent Control. This term, to my mind, refers to the hierarchical organization of the control of complex systems, with fan-in of sensor data and fan-out of actuator commands. Control and models for control are signal based at the lowest levels of the hierarchy and symbolic or event based at higher levels. The dynamics of such systems are a rich blend of automata, discrete event systems, petri nets and differential equations. Examples of such systems occur, for instance, in biological motor control in Intelligent Vehicle Highway Systems, in flight control, automotive control and in signal processing.

My talk will characterize some common features of these examples :

1. Hybrid Dynamics consisting of continuous time dynamics combined with logic.
 2. Hierarchically organized control, with the low level control being nonlinear control at the level of differential equations and the higher levels being analogous to the control of Markov chains (namely stochastic control of a finite state non-deterministic process).
 3. Distributed intelligence and adaptation at all levels of the hierarchy.
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9:30 - 10:00

Steps Towards Real Intelligence

Sanjoy K. Mitter

MIT

In this talk, I discuss why the methodology of classical AI is not the appropriate one for the design of control systems having diverse sensory inputs and a variety of output modalities. I discuss how recent work on Pattern Theory, by Grenander, Mumford, Akra and myself, has relevance to the design of layered hierarchical control systems.

10:00 - 10:45

Hybrid Models for Intelligent Vehicle Highway Systems
Pravin Varaiya
University of California

Proponents of Intelligent Vehicle/Highway System or IVHS see it as a new technology that will make a major improvement in highway transportation. Control, communication and computing technologies will be combined into an IVHS system that can significantly increase safety and highway capacity without building new roads. This talk outlines key features of one highly automated IVHS system and proposes a hierarchical control architecture for it. Hybrid models are proposed for the specification and verification of the control system design. We show how existing software can be used to verify some limited features of the design. We point to open problems in theory and software support.

11:00 - 11:45

Modeling of Flight Vehicle Management Systems
George Meyer
NASA

A Flight Vehicle Management System (FVMS) is the on-board system encompassing all automatics linking the human pilot and the air traffic control (ATC) to the actuators and sensors of an aircraft. The function of FVMS is to interpret, adapt, refine and execute the commands from the human pilot and ATC, and to provide aircraft status information feedback to both the pilot and the ATC. The complete control system composed of the human pilot, ATC and FVMS is both hybrid and reactive. Rigorous techniques for the systematic modeling, design and analysis of such systems are just emerging in the field at large. Application of such methods to the specific case of the FVMS will be explored in the lecture.

An overview of the problem will be presented first. Then the structure of a generalized multi-mode auto pilot, which provides guidance, navigation and control will be described. The function of the auto pilot is to transform tables of control points and estimates of aircraft state and wind into actuator commands. A top down approach for the modeling and design of the subsystem transforming the commands from human pilot and ATC into the tables of control points that drive the auto pilot will be outlined.

Discrete Event and Hybrid Systems

11:45 - 12:30

Failure Diagnosis Using Discrete Event Models
Stephane Lafortune
University of Michigan

In this talk, we will describe on-going work on the problem of failure detection and diagnosis for large complex systems such as Heating, Ventilation, and Air Conditioning (HVAC) systems. We propose an approach where the system is modeled using a logical (or untimed) discrete event model (LDEM) and where the different failures to be diagnosed are represented by different types of unobservable events. A methodology for building such models will be outlined. The notion of "diagnosability" of a model (i.e., of the formal language generated by an LDEM) will be defined in terms of properties of this language involving suffixes of traces that contain failure events. Necessary and sufficient conditions for diagnosability will be presented. The notion of diagnosability is related to, but distinctly different, from the notions of observability and invertibility previously addressed in the discrete event literature. Using an example of a small HVAC system, we will illustrate how to perform system diagnosis using an appropriately built finite state machine that we call a "diagnoser."

1:30 - 2:15

A Formal Model for Heuristic Rules in DEDS
Yu Chi Ho
Harvard University

Optimality in design represents the holy grail of engineering. It is perhaps often an ideal but unattainable or not cost effective goal. The modern world is full of complex system optimization problems which we cannot solve. Typical examples are discrete event dynamic systems problems in manufacturing automation or other complex man-made systems. In this talk, we propose to re-direct our optimization goal to ask a softer question with the result of leading to a quantitative model for heuristics and other ad hoc decision rules.

2:15 - 3:00

Representation of Data for Sensing, Communication, and Control
Roger Brockett
Harvard University

Much of the value of novelty associated with neural networks, fuzzy logic and expert systems, as applied to control problems, can be thought of as coming from new ways to represent the data summarizing past history, the possible control actions, the feedback laws, etc. Viewed in this way, these approaches to control suggest that a broader investigation of the question of how one can best represent data for control purposes could lead to broad framework in which these methods of control could be more usefully compared with other alternatives and might even suggest entirely different alternatives. In this talk we discuss a new class of models designed to emphasize the role of data representation in control. These models permit one to establish the relative performance of a wider variety of systems than is possible using standard approaches. It builds on recent work on hybrid systems.

4:00 - 4:45

Hybrid System Modeling, Analysis and Design

Panos J. Antsaklis

University of Notre Dame

Hybrid control systems contain two distinct types of systems, continuous-state and discrete-state, that interact with each other. Their study is essential in designing sequential supervisory controllers for continuous-state systems, and it is central in designing control systems with high degree of autonomy.

A brief introduction to the main ideas and concepts of intelligent autonomous control is first given, and the relation to hybrid control is discussed. Control systems with high degree of autonomy should perform well under significant uncertainties in the system and environment for extended periods of time. Highly autonomous control systems evolve from conventional control systems by adding intelligent components, and their development requires interdisciplinary research. For the intelligent autonomous control of continuous-state systems hybrid control is essential.

Appropriate quantitative models for hybrid control systems are needed so to identify the fundamental concepts, to analyze and understand properties important to control, and to design controllers that meet the control goals, while satisfying the design constraints. Such models are introduced here. In particular models for the plant, controller, and interface are discussed. Note that the interface must transform the plant's state vector into symbols which are representative of some "event". It must also transform control symbols (directives) issued by the supervisor into control signals which can be used by the plant. The plant together with the interface are seen by the sequential controller to be a DES, and DES techniques can be used to study such systems. For this, the interface must be chosen very carefully and this is in fact the key to being able to study, in depth, hybrid control systems. In our approach, the interface contains memoryless mappings between the supervisor's symbolic domain and the plant's nonsymbolic state space. The simplicity and generality afforded by the assumed interface allows us to directly confront important system theoretic issues in the design of supervisory control systems such as determinism, quasideterminism, and the relationship of hybrid system theory to the more mature theory of logical discrete event systems. The notion of controllability of the logical DES theory is extended to DES derived from hybrid systems, and it is then used to extend DES controller design methods and to design controllers for hybrid control systems. Computationally efficient methods to design the interface and the DES controller are of great importance and interest, as they are essential in being able to design hybrid controllers for complex plants. Convex programming methods, able to handle large problems efficiently, are of particular interest. Interface requirements expressed in terms of linear inequalities are solved to derive a set of appropriate controls that ensure that the plant DES has the property of supervisability; the method of centers, framed as a learning algorithm is used. Inductive inference protocols and the ellipsoid algorithm are used to learn appropriate symbol/event bindings in finite time for hybrid systems contained in the class of variable structure systems. Such learning procedures have a polynomial convergence time, suggesting that on line event identification is a practical technique in the control of highly complex plants.

An important challenge in control is the design of intelligent controllers for large scale physical systems, such as the ones found in automated manufacturing or chemical process control. The design of such controllers must integrate prior operator experience with a priori engineering models of the plant. The successful integration of these two knowledge domains will result in the development of hybrid control systems which perform robustly in the presence of plant variations. Such an approach is extremely valuable as it allows cooperative

interaction between human operators and machine controllers in a way which predictably improves system performance. This integration of human/machine operators of large scale physical systems is under investigation. The basic framework being advocated is itemized below:

1. Translation of Engineering Specifications/Operator Procedures into DES Models.
2. Design of DES Controller.
3. Validation of DES Controller.
4. Translation of DES Controller to Operator Procedures.

In revising the operator's original procedures, we are incorporating analytical modeling information into the procedure. It is therefore possible to use the revised procedures to generate new DES plant models, and thereby iteratively determine a set of plant procedures which the human operator can effectively use to improve plant performance. The four step protocol outlined above presents a step by step outline as to how human and machine operators can be integrated to effectively control large scale plants. Prior work in intelligent or hybrid system control has tended to focus on various aspects of this problem. Here an integrated approach is proposed.

Friday, October 1, 1993

Hybrid Systems

9:00 - 9:45

Automatica from Covers a Optimal Control
Anil Nerode
Cornell University

Hybrid systems are networks of digital programs and continuous plants under the influence of external disturbances. Hybrid control is the control of continuous plants by sequential automata. This usually means frequent changes in the continuous conventional control law applied to the plant, changes based on sensor measurements of the trajectory. This usually yields plant trajectories without smooth tangents at the discrete times when the control law ordered by the control program changes. How and when to make these control law changes is the business of the sequential automaton. Kohn-Nerode introduced a uniform model of hybrid systems as networks of automata intended to cover all variants of the notion of hybrid system in use by others.

9:45 - 10:30

Logic Control via COCOLOG
Peter Caines
McGill University

The COCOLOG (Conditional Observer and Controller Logic) system is a partially ordered family of first order logical theories expressed in the typed first order languages $(L_k; k \geq 1)$ describing the controlled evolution of the state of a given partially observed finite machine. The initial theory of the system, denoted Th_0 , gives the theory of M without data being given on the initial state. Later theories, $\{Th(o^k); k \geq 1\}$, depend upon the (partially ordered lists of) observed input-output trajectories, where new data is accepted in the form of the new axioms $AXM^{o^k}(L_k)$, $k \geq 1$. A feedback control input $U(k)$ is determined via the solution of control problems posed in the form of a set of conditional control rules $CCR(L_k)$, which is paired with the theory $Th(o^k)$. We introduce a restricted version of COCOLOG, called a system of Markovian fragments of COCOLOG, in which a smaller amount of information is communicated from one theory to the next. These are associated with a restricted set of candidate control problems, denoted $CCR(L_k^m)$, $k \geq 1$. Under weak conditions, a Markovian fragment theory $MTh(o^k)$ contains a large subset of $Th(o^k)$, which includes, in particular, the state estimation theorems of the corresponding full COCOLOG system, and, for the set of control rules $CCR(L_k^m)$, has what is termed the same control reasoning power. This supplies a theoretical basis for the increased theorem proving efficiency of the fragment systems versus the full COCOLOG systems. Finally we give some computer generated examples illustrating these results.

10:45 - 11:30

Models for Discrete-Event and Hybrid Systems
Peter Ramadge
Princeton University

Several formal models have recently been proposed for the control of a dynamical system in a hybrid (continuous and discrete) framework. At the most elementary level these systems model what might result from several forms of "intelligent control". Simple case studies of flow models have illustrated the complex nature of the closed loop dynamics; and results from the computer science community have attempted to determine the computation complexity of simple questions concerning the behavior of such systems.

This talk will review some of these models and results and speculate on what connections can be made between them.

Switched Systems

1:30 - 2:15

Logic-Based Switching: A Form of Intelligent Control

A.S. Morse

Yale University

Recent advances in system theory have shown that much can be gained by using logic-based switching strategies, together with more familiar techniques in the synthesis of feedback controls. The overall models of systems composed of such logics together with the processes they are intended to control, are concrete examples of what might be called "hybrid dynamical systems." In this talk we will describe three different hybrid systems of this type - each consists of a continuous-time process to be controlled, a family of continuous-time, candidate fixed-parameter or adaptive controllers, and an "event-driven switching logic." The first two logics called hysteresis switching and dwell-time switching respectively, are simple strategies capable of determining in real time which candidate controller should be put in feedback with a process in order to achieve desired closed-loop performance. The third, called cyclic switching, has been devised to deal with the well-known certainty equivalence stabilizability problem which arises in the synthesis of identifier-based adaptive controllers because of the existence of points in parameter space where the design model \hat{A}_p upon which certainty equivalence synthesis is based, loses stabilizability.

2:15 - 3:00

A Dynamicist's View of Hybrid Systems

John Guckenheimer

Cornell University

This lecture will present a formal mathematical definition of hybrid systems that has been implemented in a version of the computer package DsTool. An example, stabilizing an inverted double pendulum on a cart, shows the effectiveness of hybrid control strategies for solving problems that have proved difficult with more traditional methods. Remarks will be made about ongoing work to develop a general theory of the dynamics of two dimensional hybrid systems.

3:00- 3:45

Dynamic Systems and Analog Computation
Eduardo Sontag
Rutgers University

One of the most exciting challenges in current control theory and signal processing is that of formulating a rich mathematical framework in which to study the interface between the continuous (analog) world and discrete (digital) computers which are capable of symbolic processing. Successful approaches will eventually allow for the interplay of modern control with automata theory and other techniques from computer science. This is needed because, although classical control techniques have proved spectacularly successful in automatically regulating relatively simple systems, in practice controllers resulting from the application of the well-developed theory are often used as building blocks of far more complex systems. The integration of these systems is often accomplished by means of ad-hoc techniques that combine pattern recognition devices, various types of switching controllers, and humans --or, more recently, expert systems,-- in supervisory capabilities.

The need to understand the analog/digital interface has motivated much research into areas such as discrete-event systems, supervisory control, and more generally "intelligent control systems". In this context, it becomes of interest to study the behavior of dynamical systems from the point of view of classical computational theory.

This talk will briefly survey some recent work by the author and his collaborators on the study of dynamical systems as analog computing devices, as well as some related issues, such as the observability of continuous systems with restricted observations, or certain issues of control and pattern recognition by "neural nets". One may expect that such studies will become a useful component of the general approaches that will eventually emerge.

4:00 - 4:45

Trajectory Stores and Hybrid Systems
Robert Grossman
University of Illinois

This talk is concerned with a proof of concept implementation of a path planning algorithm for hybrid systems. By a hybrid system we mean a collection of nonlinear control systems, each corresponding to a mode of the hybrid system, with mode switching determined by a finite state automaton, reacting to discrete input events.

The basic idea is to create a persistent object store consisting of short duration trajectory segments and compute the desired path by a suitable query on the store. The query returns a concatenation of short duration trajectory segments which is close to the desired path. The needed short duration segments are computed by using a divide and conquer algorithm to break up the original path into shorter paths; each shorter path is then matched to a nearby trajectory segment which is part of the persistent object store by using a suitable index function.

In order to obtain near-real time performance, we developed a scalable persistent object store called pool which is optimized for scientific computing in high performance computing environments.

In this work, we use the observation space representation of a hybrid system. Roughly speaking, this may be viewed as dual to the state space representation. This representation is a very basic one: it forms the basis for the Heisenberg picture in quantum mechanics; it has

been used to model discrete time control systems by Sontag and continuous time control systems by Bartosiewicz. The advantage for us is that hybrid systems can be defined as suitable products of continuous nonlinear control systems and discrete automata.

Path planning algorithms for control systems generally proceed by concatenating trajectory segments of a fixed, specialized type. This provides enough structure so that controls can be computed which approximate the path. The cost of computing the path is essentially the cost of computing these controls. For example, a path planning algorithm by Murray and Sastry employs trajectories which are sinusoids at integrally related frequencies. In contrast, the approach proposed in this talk exploits large numbers of trajectory segments of a general type which are computed during a precomputation. The computation of the path requires only a low cost selection of the most appropriate trajectory segments. The more general type of trajectory segment makes it easier to match the desired path. In essence, space is traded for time: large amounts of space are required to store all the precomputed trajectory segments, but the cost to approximate the path is low.

The talk covers joint work with Richard Larson, Dimitrios Valsamis and Xiao Qin.

Saturday, October 2, 1993

Representative Systems

9:00 - 9:45

From Discrete Event Processes to Hybrid Systems
Michael Heymann
Technion

From Discrete Event Processes to Hybrid Systems Hybrid systems are viewed as objects that consist of two communicating modules: a reactive module, in which discrete state changes occur in response to events that are generated either internally or by the environment, and a transformational module, that responds temporally to discrete or continuous-time signals. In the most general case, the two modules are strongly intertwined and affect each other's internal operation. In simpler situations only one of the modules is affected by the operation of the other, while the other is not. We call such systems unilateral hybrid systems.

In its simplest version, the reactive module of the system consists of a Discrete Event Process (DEP), i.e., a simple state transition system, but in general the reactive module may be more complex. The transformational module of the system is generally a (continuous-time or discrete-time) dynamical system in which changes occur in response to time evolution.

We shall consider four classes of systems - DEP, (statically) Timed DEP, Dynamically timed DEP, and (fully) Hybrid systems. In contrast to the first three classes of systems which are unilateral and only the reactive module is affected by the transformational module when it exists, the fully hybrid system is one in which the transformational module is also effected by the reactive module.

Several research issues will be discussed. As an example, a preliminary State-charts model of an autopilot mode-management system will be briefly described.

9:45 - 10:30

Intelligent Aircraft/Airspace Systems
Robert Stengel
Princeton University

Air transportation provides the backbone for passenger transport over moderate to long distances in the U.S. and much of the world, and it is becoming an increasingly important mode for short-range travel and cargo transport as well. There is a growing demand for use of available airspace and a heightened concern for on-time performance. Demand frequently exceeds available capacity of the airspace system, causing flight delays, negative economic impact, and passenger inconvenience. New technologies are emerging that will make flight operations both simpler and more complex. On the one hand, advances hold promise for increasing the productivity, reliability, and safety of the air transportation system. On the other, advances in technology introduce uncertainty, increase human workload (if not properly implemented), increase the potential for dispute, and present new challenges for both certification and day-to-day operations.

This paper presents a concept for an Intelligent Aircraft/Airspace System (IAAS) that could be a focal point for developing air traffic management in the coming decades. The IAAS would integrate the capabilities of all ground-based and airborne components of the system (identified as Intelligent Agents) in order to provide increased capacity and maintained or improved safety. Principled Negotiation is proposed as a framework for interactions between intelligent agents.

10:45 - 11:30

Multiple Agent Hybrid Control System
Wolf Kohn
Intermetrics, Inc.

This talk overviews a formal approach for the design, analysis and implementation of hybrid control systems. Hybrid control systems are characterized by the presence in their architecture of at least one reasoning module, that is, a device whose function is to infer from stored dynamic or static knowledge a course of action. Reasoning modules are referred to as Hybrid Controllers.

Hybrid Controllers are necessary elements in the implementation of autonomous systems. The main distinguishing functional characteristic with respect to conventional control systems is the ability to Redesign on-line the control law. This capability is needed for a variety of reasons such as responding to unexpected behavior of the system or its environment, for improving performance when enhanced knowledge about the system or its environment become available through sensory observation, for responding to changes in the goal of the system, for decreasing the behavioral effects of structural uncertainty, and others.

The hybrid controllers we will describe in this talk are termed declarative controllers. In these controllers, intelligence is provided by a reasoning procedure whose central element is a customized Equational Logic Inferencer. This inferencer operates on a Knowledge Base whose elements are equational clauses.

We will show that the expressive power of the equational clause format is well suited for the representation of dynamics, requirements, computational (Real-Time) constraints and heuristic and empirical principles. These types of knowledge are required in the formal design and implementation of autonomous control systems.

The inferencer in a declarative control implements a deductive proof strategy. During operation of the controller, a query is always present. A query is generated by an internal module, called the planner, when prompted by another module, called the adapter. The query at any instant of time represents the Desired Behavior of the system throughout the time interval for which it is valid i.e., until the behavior it represents is no longer logically compatible with the status of the knowledge base. Each query proved by the inferencer states the desired closed loop behavior as an optimization problem. The proof is carried out by constructing and executing an automaton termed The Proof Automaton.

The bulk of the talk is devoted to an overview of the main operational characteristics of Declarative Controllers, illustrating them with examples, and presenting some preliminary results about their structure and dynamics. We will also attempt to establish some general directions of future research in this area.

11:30 - 12:15

Challenges in Flight Control

John Hauser

University of Colorado

The pursuit of high performance and maneuverability in aerospace vehicles continues to present difficult challenges to the control system designer. Not only must future vehicles be capable of rapid transitions over a large operating envelope, they must also be able to accommodate a variety of mission objectives and different physical aircraft configurations. Using an extremely simple aircraft model, we will discuss several of these issues and provide some techniques that may be used to help guarantee successful operation of such aircraft.

Neural & Fuzzy Systems--Soft Computation

1:30 - 2:15

Fuzzy Control in Control Engineer's Tool Box

Masayoshi Tomizuka

University of California

In the design of control systems, the controlled plant and control objectives must be well understood before any methodology is attempted. There is not a universally best methodology for solving every problem. At the same time, there may be more than one approach to solve a problem. The fuzzy rule based or fuzzy logic approach has proven its value in the design of certain control systems. Although, the approach is often referred to as fuzzy control, it has two components: "rule or logic base" and "fuzzy set theory." Experts' knowledge or good ideas can often be described by a set of rules. The development of rules for a controlled plant is supported by the designer's good understanding of how the system works. The fuzzy set theory provides a means to transform a set of rules to a computer implementable control algorithm. Two things should be noted here: one is that the designer must have a model (implicit model) although it may not be in the differential equation form, and the other is that the fuzzy set is a friendly interface to humans to describe and convert his/her knowledge to control algorithms. In fact, good "engineering" or "ideas" appear to be always behind the successful implementations of fuzzy control. The use of a fuzzy rule based approach is not limited to signal regulation level, which is often only one aspect of the control/automation of a system. Fuzzy logic is an attractive method for higher level

controls such as coordination of various sub-controllers, each of which is designed for a different objective. A simple but instructive example for this is swinging-up and stabilization of inverted pendulum systems. Fuzzy counterparts of various conventional control methodologies, such as predictive control and adaptive control, have been reported. While the fuzzy counterparts do not necessarily use the same or even similar algorithms when compared with conventional methodologies, the motivation and goals are common. It is expected that increasing attention is being directed to the blending of conventional control and fuzzy control. An obvious example is the use of fuzzy boundaries in gain scheduling and variable structure systems. Stability assurance is desired in any control system. Apart from fuzzy control, is it always possible to assure stability when it comes to control of physical systems? Recognizing that a recent trend in control theory is to develop design tools for systems with a variety of uncertainties, extensive testing is often required as the final check for stability and performance.

2:15 - 3:00

Modeling and Control of Hierarchical Systems with Fuzzy Logic

L.X. Wang

University of California

Fuzzy systems have a dual role: on one hand, they are rule-based systems constructed from a collection of fuzzy IF-THEN rules; on the other hand, they are nonlinear mappings which have nice mathematical properties like universal approximation. One contribution of fuzzy logic is that it provides a systematic procedure of transforming a rule base into a nonlinear mapping. In this paper, we use fuzzy systems to model higher levels of hierarchical systems. Specifically, we consider three-level hierarchical systems where the lowest level comprises the plant and conventional feedback controllers, the middle level performs supervisory operations to guarantee the stability of the whole system, and the top level is a planning level which provides control targets for the lower levels and communicates with the environment. The plant is modeled by differential equations, and the supervision and planning levels are modeled by fuzzy systems. The advantage of such model is that all the levels are formulated in the same mathematical framework (due to the dual role of fuzzy systems), therefore it is possible to analyze the hierarchical systems in a mathematically rigorous fashion. Two theoretical questions introduced by this model are studied in this paper: 1) how to specify the supervisory rules (i.e., how to design the fuzzy systems modeling the supervision level) such that the whole system is stable, and 2) how to design and update the fuzzy systems modeling the planning level such that the whole system achieves its objectives and is adaptable to new environment and new objectives. Two case studies are presented: intelligent vehicle/highway systems, and integrated planning/control of mobile robots.